Laboratory-based Photoemission Spectro-microscopy at 71.7 eV and 113.7 eV for Studies of Complex Materials

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Motivation: Intense EUV Light Sources

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Photoemission spectroscopy—from early days to recent applications

Friedrich Reinert[1,3] and Stefan Hüfner[2]

"Furthermore, one can hope that in the future there will be intense and continuous light sources available for the laboratory, which will end the necessity to move to synchrotron radiation facilities for numerous photoemission applications."

Friedrich Reinert, 2005, doi:10.1088/1367-2630/7/1/097

Motivation: Intense EUV Light Sources

- Standard sources for UPS limited to 40.8 eV, but problems arise:
  - e.g. final state effects

- For XPS, X-ray tubes are used
  - Long integration times (small interaction cross sections)
  - No UPS

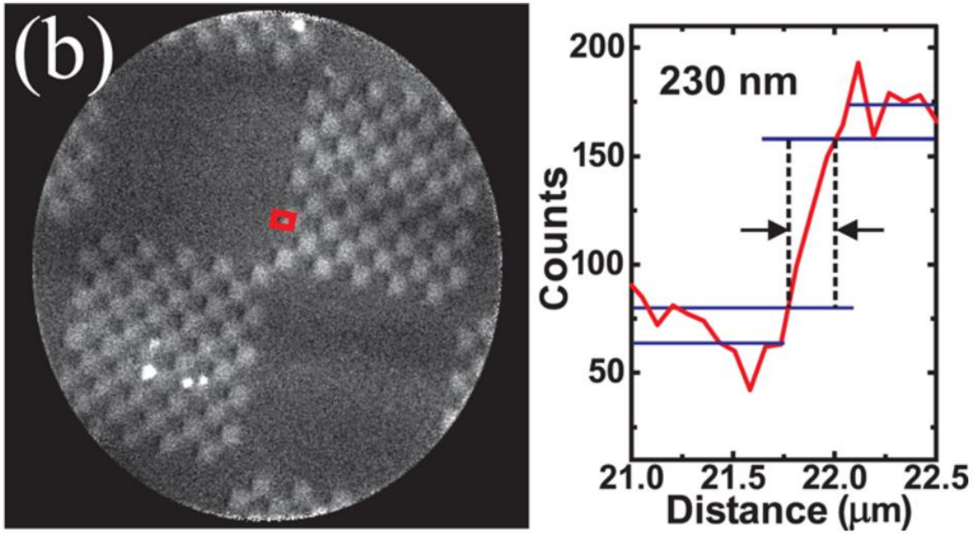
	Laboratory Light Sources	Photon Energy Range
UPS	UV-Laser	4.66 eV
	Hg-Lamp	4.9 eV
	He I/II	21.2 eV / 40.8 eV
UPS & XPS	HHG	~ 100 eV
	DPP-Source	Up to 620 eV
XPS	X-ray Tube	1488 eV (K_α)

Motivation: Intense EUV Light Sources

- Standard sources for UPS limited to 40.8 eV, but problems arise:
  - e.g. final state effects
- For XPS, X-ray tubes are used
  - Long integration times (small interaction cross sections)
  - No UPS
- HHG sources suffer from extreme space charge effects
  - Short EUV pulses -> extremely high PE densities
  - Coulomb repulsion at crossings
  - Temporal, lateral & energy broadening

UPS & XPS

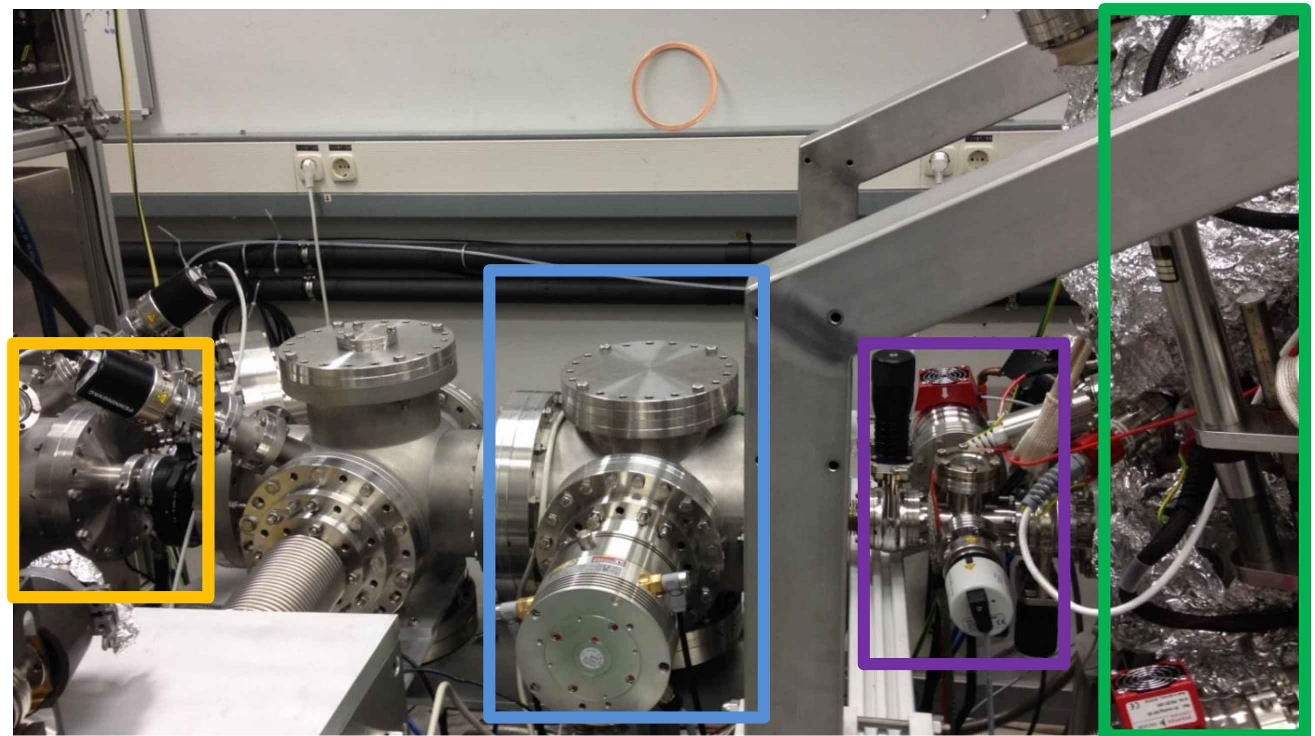
HHG	~ 100 eV
DPP-Source	Up to 620 eV

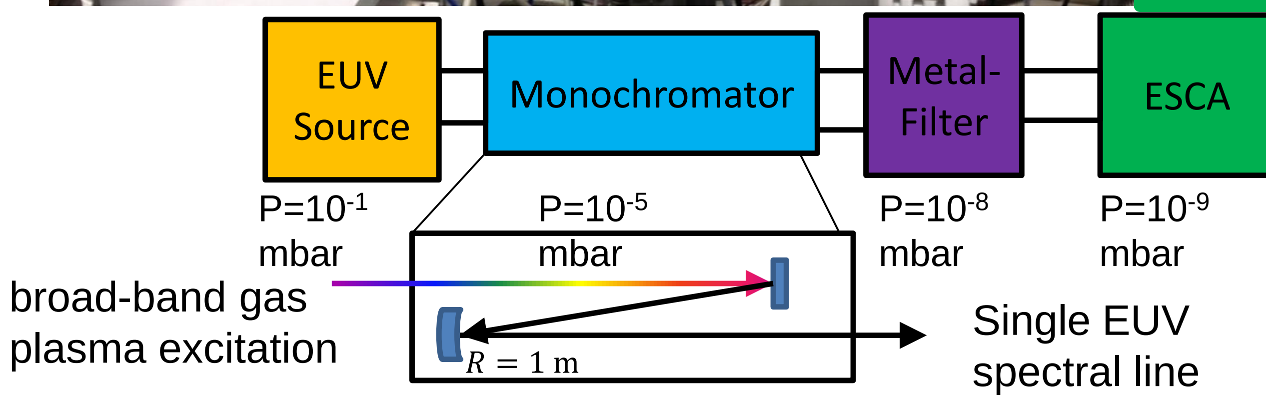


Time-of-flight-photoelectron emission microscopy on plasmonic structures using attosecond extreme ultraviolet pulses, Chew et al. 2012
Integration time: 1.5 h, $E_\gamma = 93$ eV

Setup

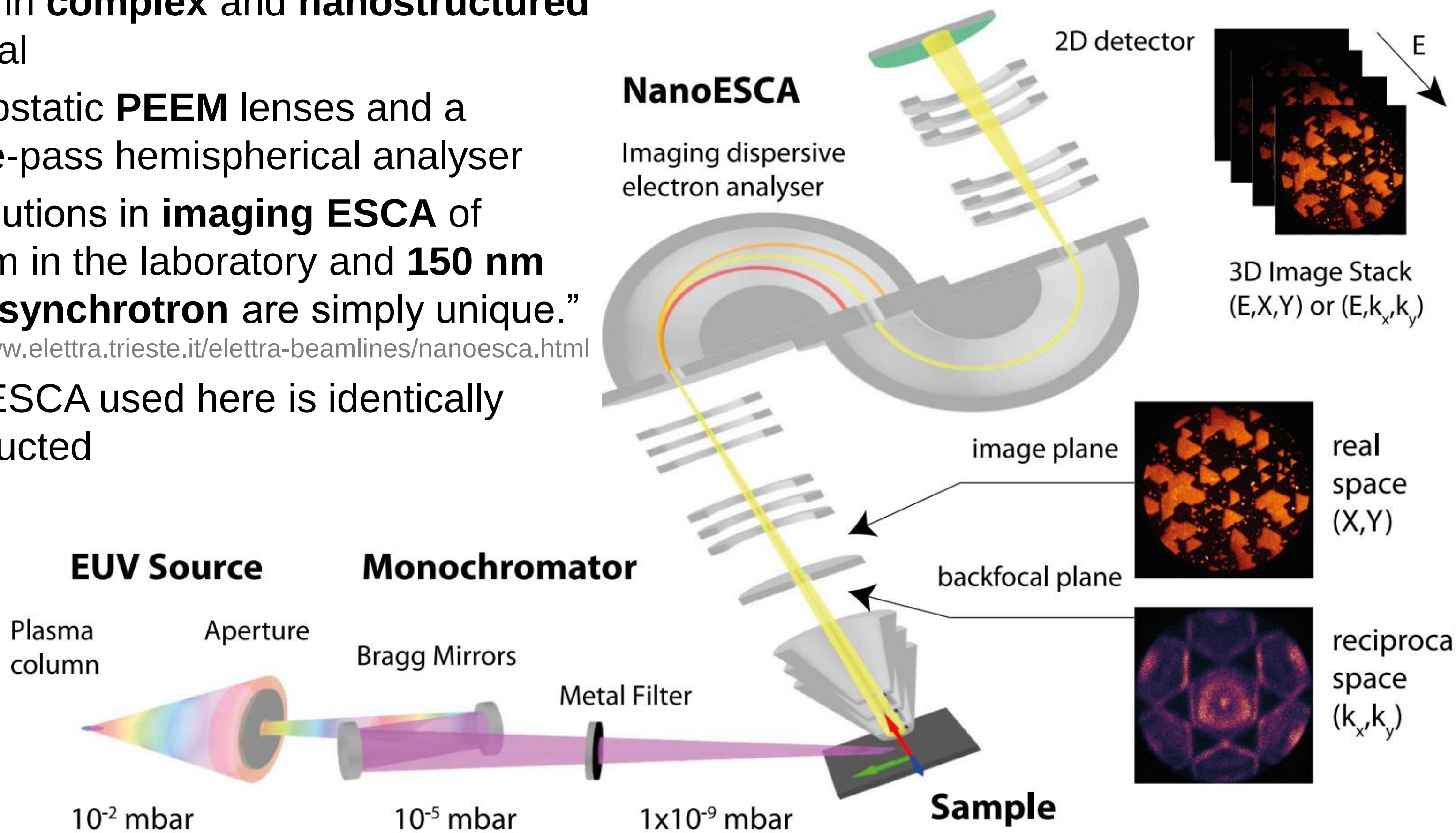
- $E_\gamma = 71.7\ \mathrm{eV}$
- $E_{PP} = 1.32\ \frac{\mathrm{mJ}}{2\pi\ sr}$
- $\bar{I} = 2.64\ \frac{W}{2\pi\ sr}$
- On sample:
  - $1.8 \cdot 10^{11}$ photons/$(\mathrm{mm}^2\mathrm{s})$





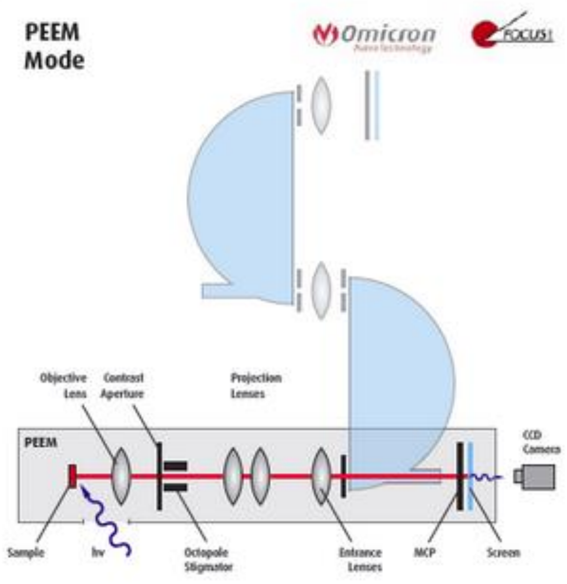
The NanoESCA

- Analysis of chemical and electronic states in **complex** and **nanostructured** material
- Electrostatic **PEEM** lenses and a double-pass hemispherical analyser
- “Resolutions in **imaging ESCA** of 650 nm in the laboratory and **150 nm** at the **synchrotron** are simply unique.”
  https://www.elettra.trieste.it/elettra-beamlines/nanoesca.html
- NanoESCA used here is identically constructed



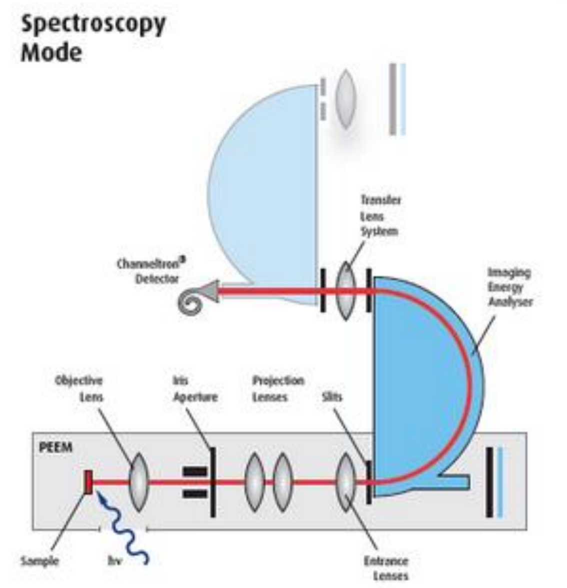
Modes of the NanoESCA

Where are the interesting features?



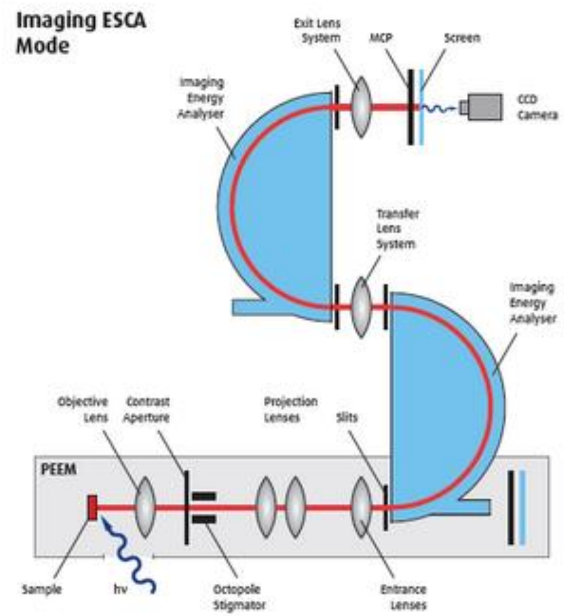
Photoelectron Emission Microscope mode

Which elements are there and how much?



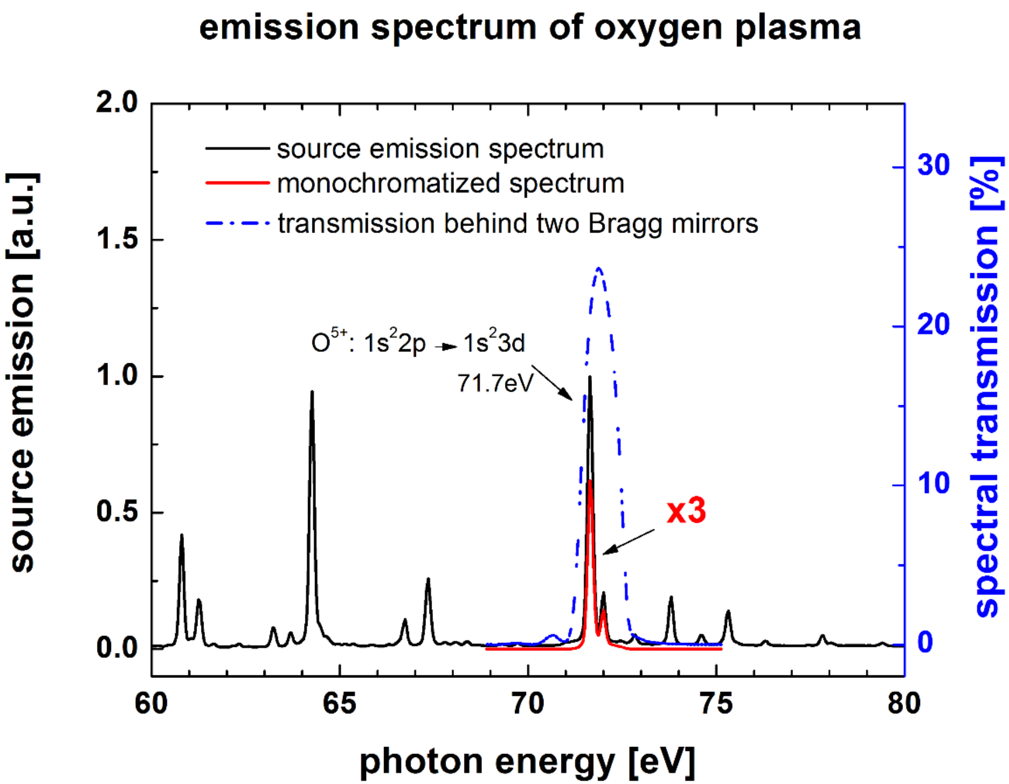
Small Spot Spectroscopy mode

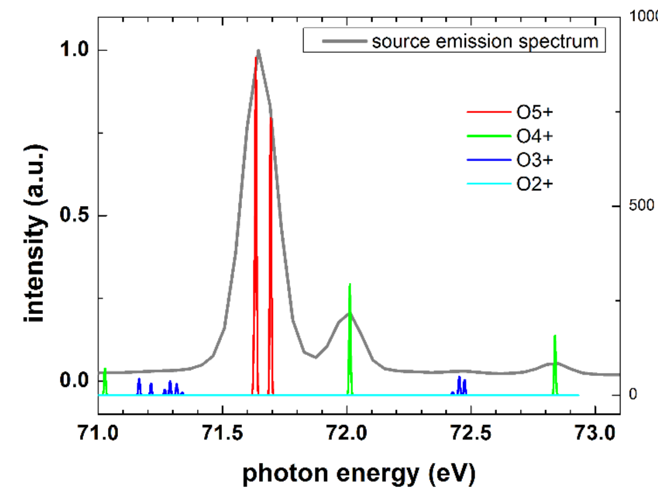
What is the elemental map?



Imaging ESCA-Mode

EUV spectrum (oxygen) behind Bragg mirrors

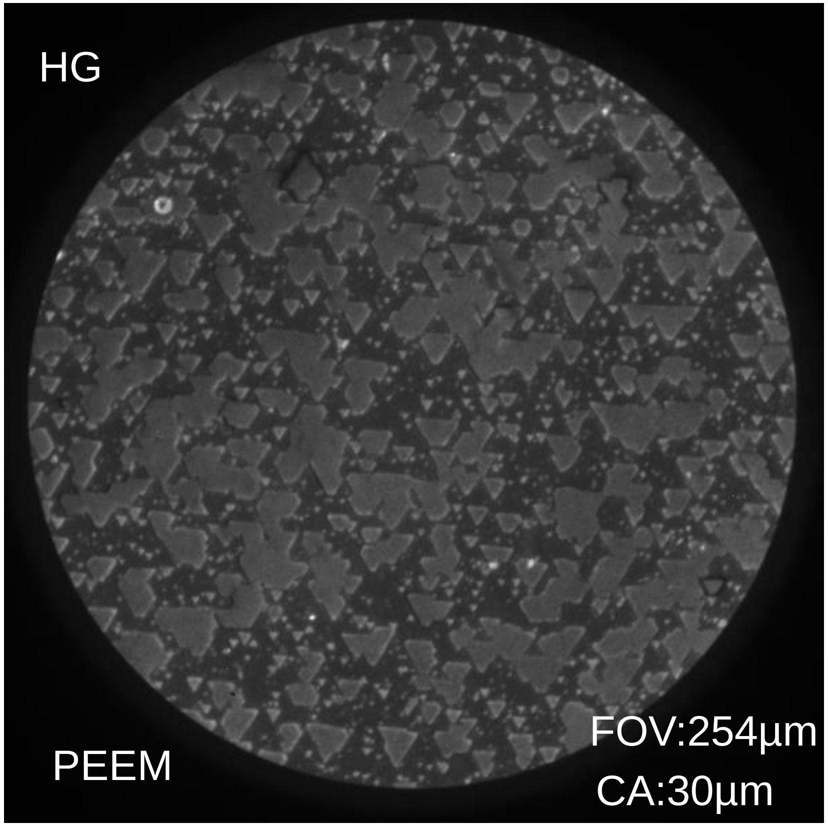


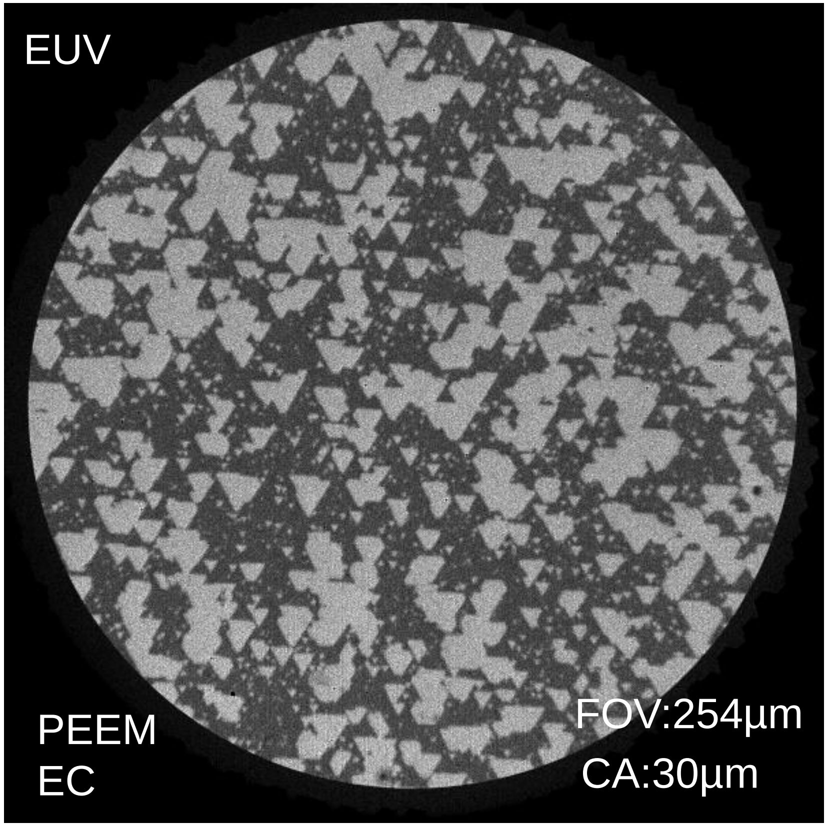


- Doppler broadening[1]: ~ 13 meV
- O^{5+} separation: 60 meV
- Distance to O^{4+}: < 400 meV
  - Effect from satellite does not affect measurements
- Bragg mirrors from optiX fab.

[1]Saha LTE spectrum from NIST database: $T_e = 10$ eV, $n_e = 10^{18}$ cm^{-3}

PEEM mode: Features of GeSbTe (GST)





Spectroscopic opportunities in the lab

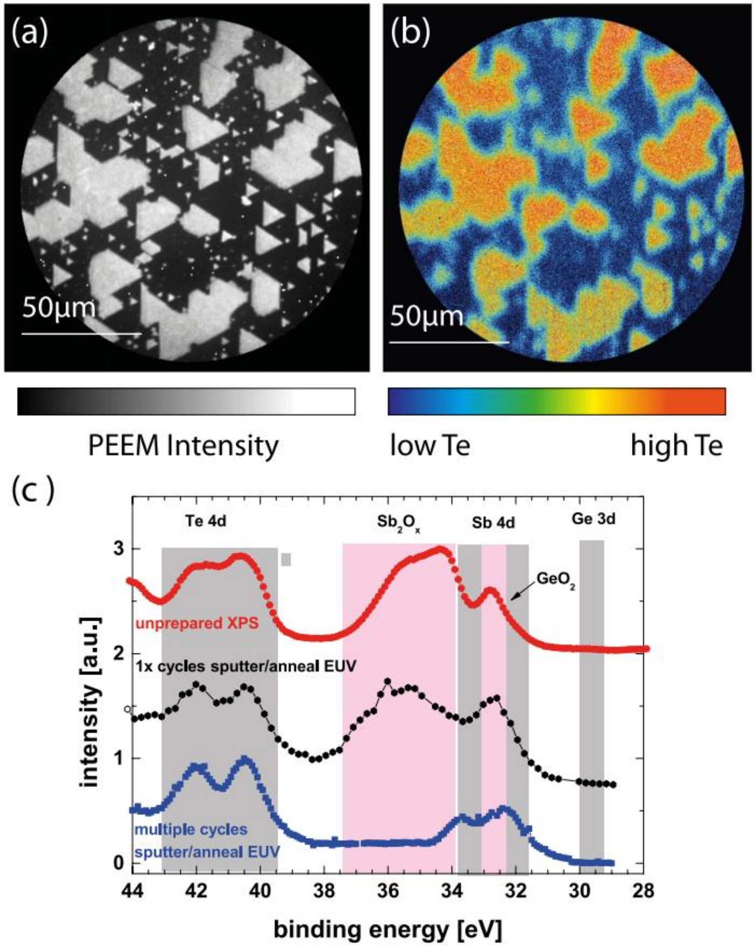
Study of epitaxially grown crystalline hexagonal Ge-Sb-Te (GST,1:2:4) islands on Si (111).

Focus: Surface oxidation

a) EF-PEEM image at 5.2 eV (Hg)

b) EF-PEEM images from 39 – 41 eV (Te 4d) show regions of high Te concentration
   - $E_{\gamma} = 71.7$ eV
   - $t_{integration} = 1$ s per image

c) Spectrum extracted from images
   - Black: Oxidized Sb peak visible
   - Blue: sputtered/annealed sample
   - Red: Standard XPS with Al-Kα

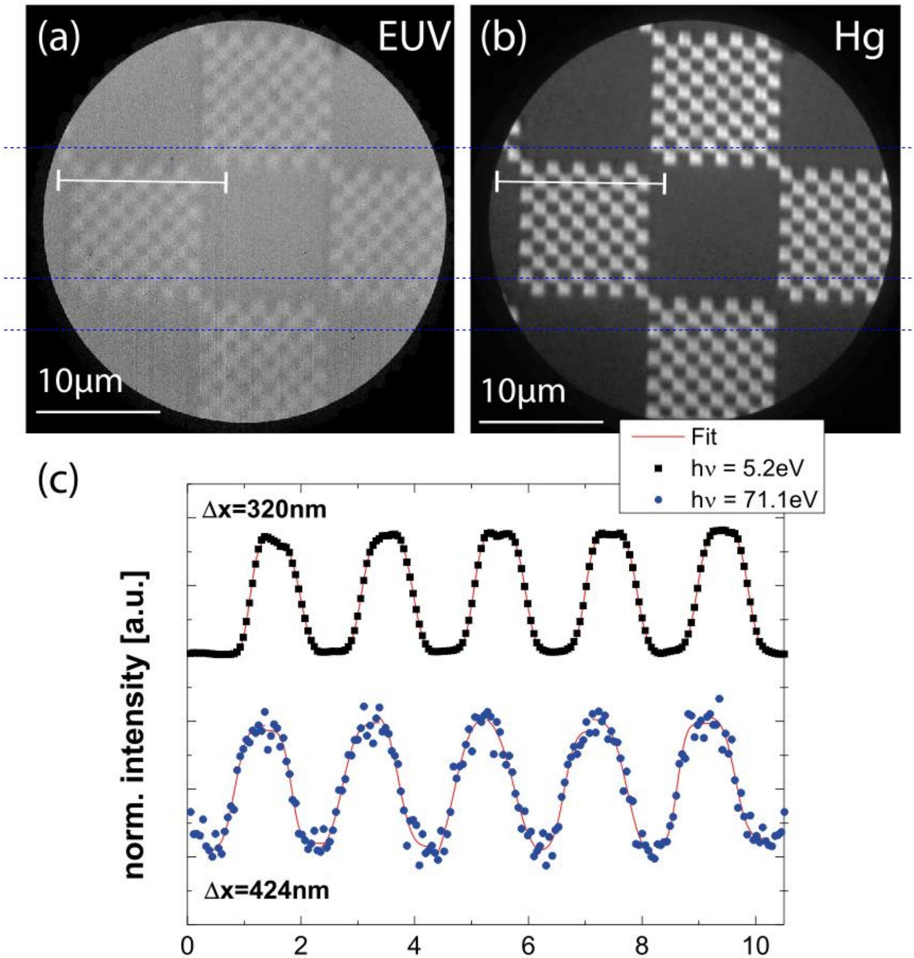


- Standard XPS lead to same results

Resolution in energy filtered (EF) PEEM mode

- Sample: chessboard calibration
- Au fields $1\ x\ 1\ \mu m^2$
  a) EF-PEEM: $E_\gamma = 71.7\ eV$
  b) EF-PEEM: $E_\gamma = 5.2\ eV$
  c) Line scans for each picture

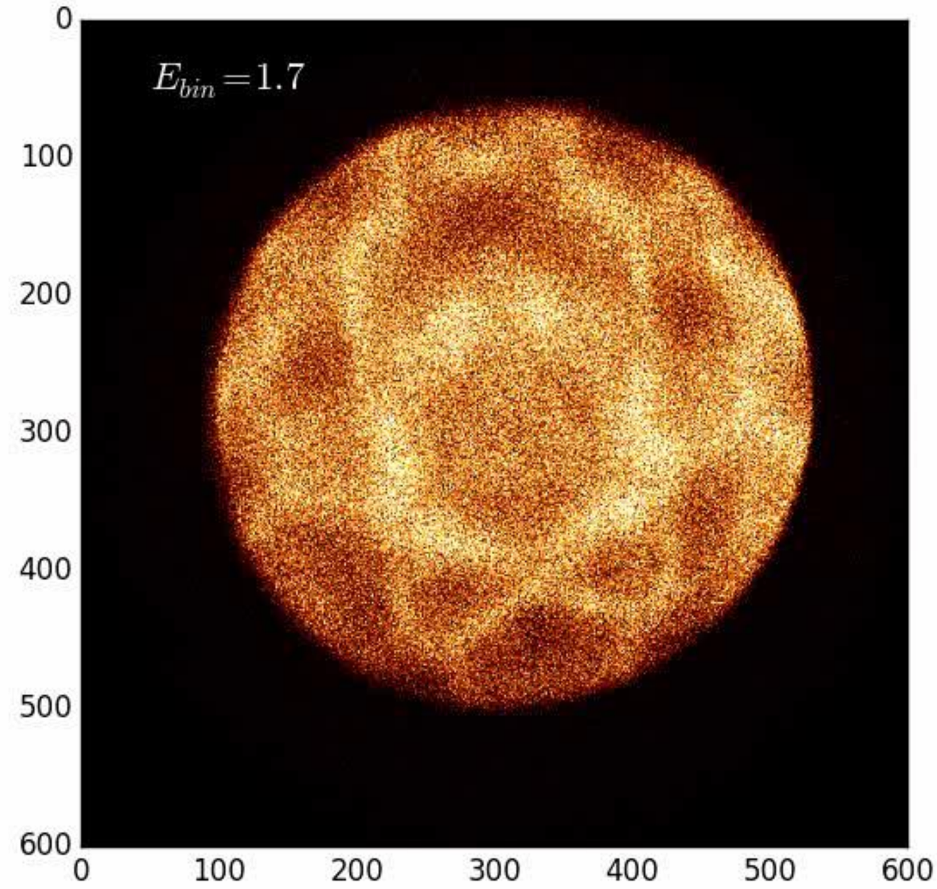
- Contrast is low for $E_\gamma = 71.7\ eV$
  - Core levels of Si & Au out of range
- Resolution is still comparable:
  - $\Delta x = 320\ nm\ (HG)$
  - $\Delta x = 424\ nm\ (EUV\ 71.7\ eV)$



k-Space measurements with 71.7 eV

- Maximum field of view: $5.6\ \text{A}^{-1}$
  - 2.4 Brillouin zones of Au (111)
  - Six fold symmetry

- Energy resolution ~ $400\ \text{meV}$ from electron analyzer
  - Two emission lines at 17.3 nm
    - approx. $15\ \text{meV}$ linewidth
    - $60\ \text{meV}$ distance



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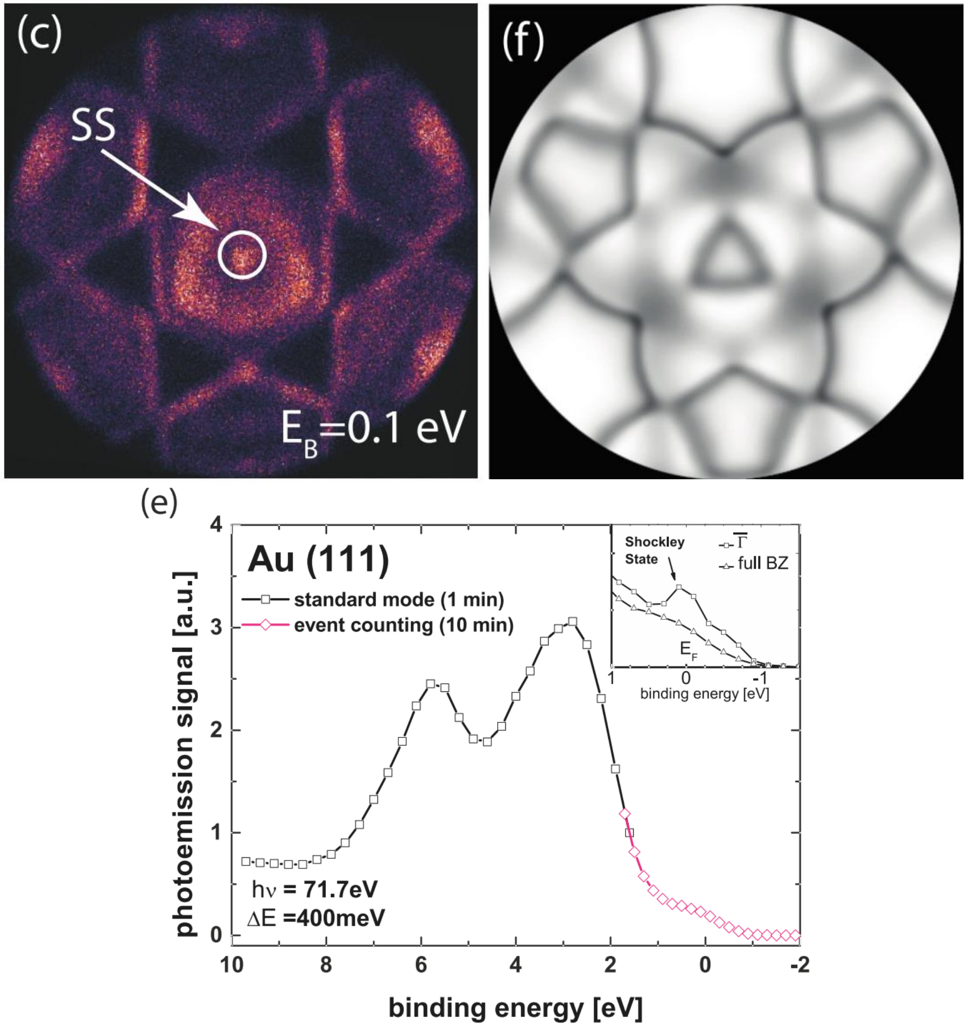
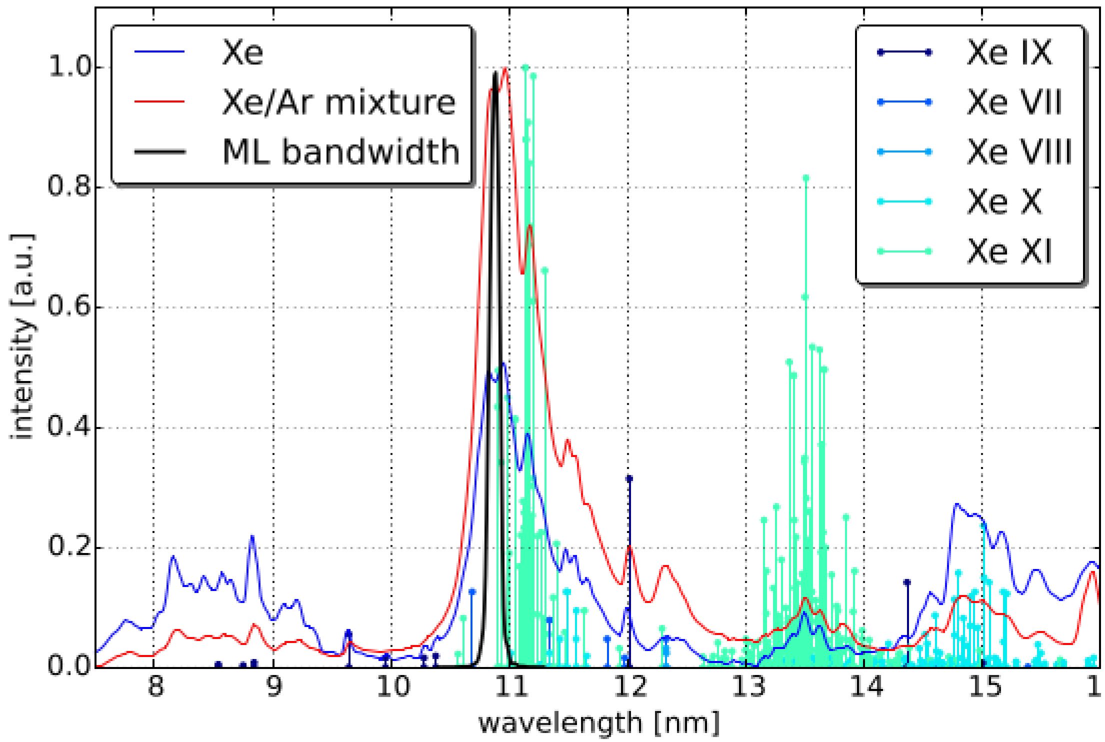
- Surface states occur only at the sharp transition from solid material that ends with a surface



High flux from Xe 10.9 nm UTA

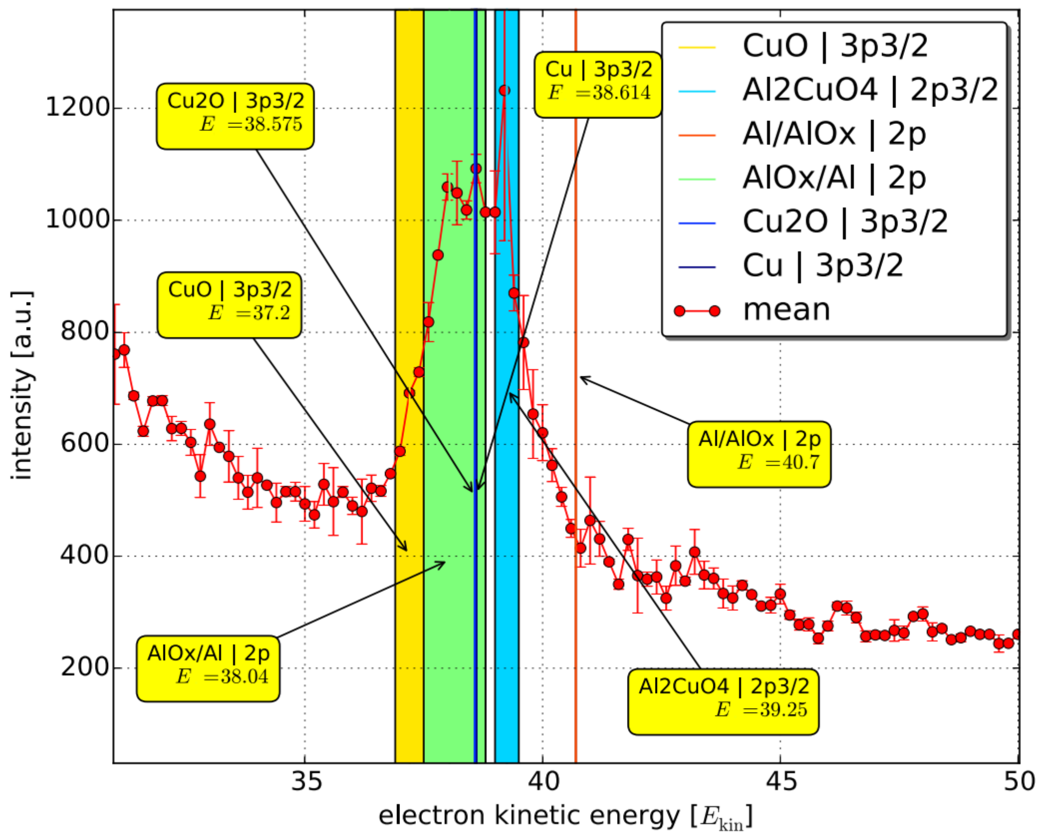
- Adding Argon to Xenon results in enhanced emission at 10.9 nm (113.7 eV) by suppressing lower and higher wavelengths.

- 2x small-bandwidth ML-mirrors
  - $\Delta\lambda_{FWHM} = 0.1$ nm
  - $\Delta E_{FWHM} = 1$ eV
  - $R_{peak} = 13$ %



Debris analysis: EUV source exposure sample

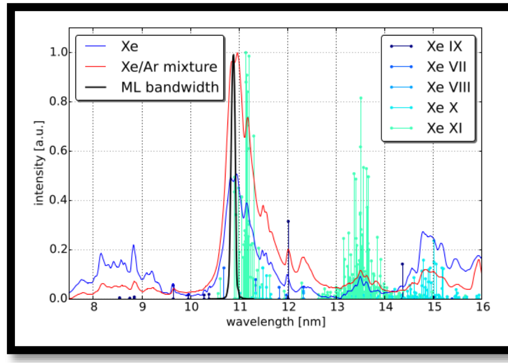
- Sample has been exposed to a LPP EUV source
- PES ($E_\gamma = 113.7$ eV) shows one broad peak at $E_{bin} = 75$ eV
- Elements found fit perfectly to EUV source & sample history
  - Cu, Al
- Measurement time (complete range): 10 min

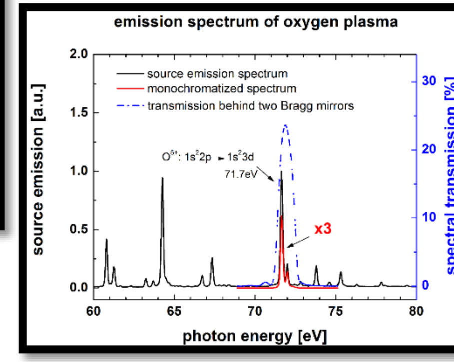


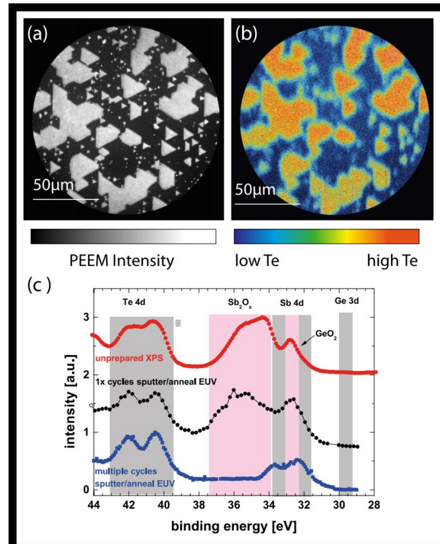
Summary & Outlook

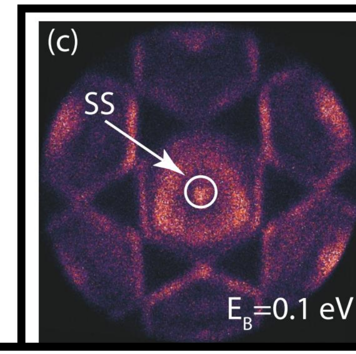
- High power EUV gas discharge sources are well suited for UPS/XPS/PEEM
  - High flux
  - Extreme narrow emission lines
  - Reasonable pulse duration
  - Tunable spectrum
  - Highly surface sensitive
  - Multiple beamlines possible

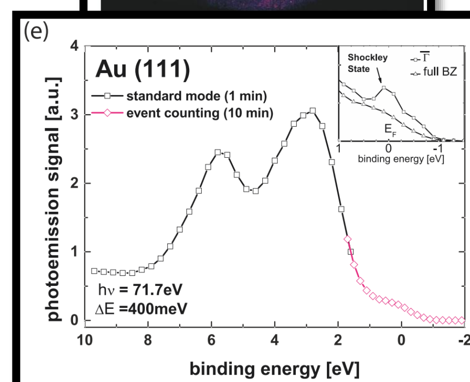
- Future outlook:
  - More sophisticated optics
  - Improvement of EUV emission characteristics

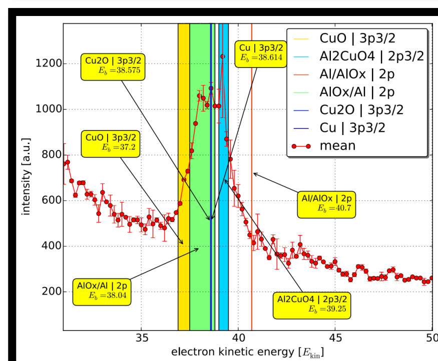












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  - Martin Schuck